THE IMPACT ON ELECTRICAL CONDUCTIVITY MEASUREMENT DUE TO SOIL PROFILE PROPERTIES, SHALLOW HYDROLOGIC CONDITIONS, FERTILIZER APPLICATION, AGRICULTURAL TILLAGE, AND THE TYPE OF GEOPHYSICAL METHOD EMPLOYED

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Abstract

Precision agriculture is a growing trend, allowing the right amount of fertilizer, soil amendments, pesticides, herbicides, and tillage effort to be applied to different field areas, thereby optimizing crop yields while reducing input costs. Field crop yield variations are often strongly correlated with spatial soil fertility patterns. The intrinsic fertility of a soil is itself affected by various soil profile properties, such as salinity, organic matter content, cation exchange capacity, grain size distribution, clay mineralogy, claypan/fragipan depth, etc. Apparent soil electrical conductivity (ECa), mapped in situ with geophysical methods, can potentially be used to gauge spatial changes in soil fertility, since it is influenced by these very same properties. However, other factors related more to agricultural field operations also possibly impact ECa, and examples include shallow hydrologic conditions affected by irrigation/drainage (or rainfall), changes in soil nutrient levels from fertilizer application, and alteration of soil density near the surface due to normal tillage operations.

The ECa impact of these other factors compared to soil profile properties were investigated primarily through electromagnetic induction (EMI) surveys on a test plot where a series of field condition modifications were undertaken. Here, the average EMI EC_a correlated moderately well with average soil surface volumetric moisture content (r^2 = 0.67), but not with average shallow water table depth (r^2 = 0.00). Factoring in the soil surface moisture conditions present, high fertilizer applications appeared to modestly increase the average test plot ECa. Soil tillage, though, had minimal influence. The spatial patterns shown in the EMI generated maps generally remained consistent, regardless of test plot field conditions, indicating soil profile properties dominated the ECa response. EMI and two different pulled electrode array resistivity methods were then tested on two other test plots, and with respect to spatial ECa patterns, all three techniques provided similar results.

Introduction

Precision agriculture typically combines geospatial datasets, state-of-the-art farm equipment technology, and global positioning system (GPS) receivers to provide variable rate field application of fertilizer, soil amendments, pesticides, herbicides, and tillage effort. The benefits of precision agriculture to farmers are maximized crop yields and reduced input costs. There is an important environmental benefit as well. Over-application of agrochemicals and soil tillage is fairly common. Since precision agriculture methods result in just the right amount of fertilizer, soil amendments, pesticides, herbicides, and tillage effort to be applied to different parts of the field, there are less agrochemicals and sediment in the runoff entering local waterways. Geospatial information on soil fertility helps in determining the proper application of agrochemicals or tillage effort. Various soil profile properties, such as salinity, organic matter content, cation exchange capacity, grain size distribution, clay mineralogy, claypan/fragipan depth, etc. all influence soil fertility, and likewise the measured soil electrical conductivity. Consequently, by mapping apparent soil electrical conductivity (ECa) using geophysical methods, spatial patterns of soil fertility can potentially be inferred. However, other factors related more to agricultural field operations also possibly impact ECa geophysical measurements and need to be carefully considered. Examples of these agricultural field operations related factors include shallow hydrologic conditions affected by irrigation/drainage (or rainfall), changes in soil nutrient levels from fertilizer application, and alteration of soil density near the surface due to normal tillage operations.

Near-surface geophysical methods, particularly those capable of mapping soil electrical conductivity, are gaining more widespread use in agriculture. In addition, an increasing amount of research within this area continues to document possible uses and limitations for employing geophysical methods to map soil electrical conductivity. There has been a substantial amount of study to date focused on demonstrating that ECa mapping is an effective tool to gauge the magnitude and spatial variability of soil salinity (Lesch et al., [1]; Hendrickx et al., [2]; Doolittle et al., [3]). Research results are mixed concerning the value of using ECa geophysical measurement techniques to monitor soil moisture. Scanlon et al. [4] evaluated ECa measured with electromagnetic induction (EMI) methods as a reconnaissance technique to characterize unsaturated flow in an arid setting and determined that the magnitude of the impact of moisture content on ECa was dependent on the geomorphic setting. An investigation conducted by Sheets and Hendrickx [5] in an arid region of southern New Mexico discovered a linear relationship to exist between ECa and moisture content in the top 1.5 m of the soil profile. However, in a field study near Quebec City, Canada carried out with traditional resistivity methods, Banton et al. [6] found that the ECa mean and spatial pattern did not change significantly between wet and dry soil conditions. The study by Banton et al. [6] also determined that ECa was moderately correlated with soil texture and organic matter, but not with porosity, bulk density, or hydraulic conductivity. Doolittle et al. [7] determined a way to estimate clay pan depths in a Missouri soil based on ECa values obtained with EMI methods. Furthermore, Fraisse et al. [8] were able to define claypan soil management zones with a combination of topographic elevation and EMI ECa data. Kravchenko et al. [9] likewise employed this combination of topographic elevation and ECa (obtained from pulled electrode array resistivity methods) to map soil drainage classes. Inman et al. [10] found that EMI ECa and ground penetrating radar data when used together can be a promising soil survey technique. Jaynes et al. [11] estimated herbicide partition coefficients based on EMI ECa measurements. In addition, Eigenberg and Nienaber [12] established that EMI ECa could be used as a way to detect field areas with high soil nutrient build-up. Consequently, a continually growing body of research is discovering new, potentially valuable agricultural applications for ECa mapping.

As is apparent from this discussion of prior research, soil electrical conductivity can be affected by a number of different items, some of which are more dominant than others depending location, climate, etc. For geophysical ECa mapping to be determined useful as a soil fertility guide within a particular region, the relative impact of the soil profile properties on spatial ECa patterns have to be far more important than that of the factors due to agricultural field operations or rainfall events. Geophysical ECa mapping for soil fertility agricultural purposes will therefore have to be evaluated on a region-by-region basis. In addition, to ensure confidence among farmers, the various different geophysical methods for measuring ECa need to provide consistent results relative to one another. Keeping all of this in mind, the two objectives of the project described in this paper were, for a typical Great Lakes region locale with glacially derived soils, (1) to determine the relative impacts on ECa due to soil profile properties versus factors associated with agricultural field operations or rainfall, and (2) to gauge the consistency between different geophysical methods used to map ECa. The starting research hypothesis can therefore be stated accordingly, "For this particular Midwest regional setting, the spatial ECa field pattern will be dominated by soil profile properties and remain similar regardless of the geophysical method utilized."

Equipment

Three different near-surface geophysical techniques for measuring the apparent soil electrical conductivity (ECa) were evaluated. Electromagnetic induction (EMI) was one method, and the other two were different versions of a pulled electrode array resistivity method. The electromagnetic induction surveys were conducted with a Geophex, Ltd. GEM-2 multi-frequency ground conductivity meter (GCM) (**Figure 1a**). During use, the GCM was held approximately 1 m above the ground in the vertical dipole position, and its base measurement period was set at 0.033 sec. EMI data were collected at frequencies of 8190, 14610, and 20010 Hz. One of the pulled electrode array resistivity measurement devices utilized for this project was a Geometrics, Inc. OhmMapper TR1 (**Figure 1b**). This unit is a capacitively-coupled, towed dipole-dipole electrode array, resistivity measurement system capable of continuous data collection at time intervals as short as 0.5 sec. In this study, the two array dipoles, each comprised of coaxial cables and transmitter/receiver electronics, one for measuring current and one for measuring voltage, were both 5 m in length. Changing the rope separation distance between the dipoles within the array altered the depth of measurement. Separations of 0.625, 1.25, 2.5, and 5 m were tested. The second pulled electrode array resistivity method employed a system developed by Veris Technologies. With this unit, the electrodes are mounted on a steel frame and comprised of 43 cm diameter steel coulters (disks) that cut through the soil to depths of approximately 2.5 to 7.5 cm as they are pulled along behind a vehicle at field speeds of up to 25 km/h. The data-logging interval is 1 s and measurement locations are determined using an integrated global positioning system (GPS). The Veris 3100 Soil EC Mapping System (**Figures 1c and 1d**) that was used in this study has six coulters with non-adjustable spacing, thereby providing two Schlumberger electrode array configurations, one for mapping the top 30 cm of the soil profile and the other for mapping the top 90 cm of the soil profile.

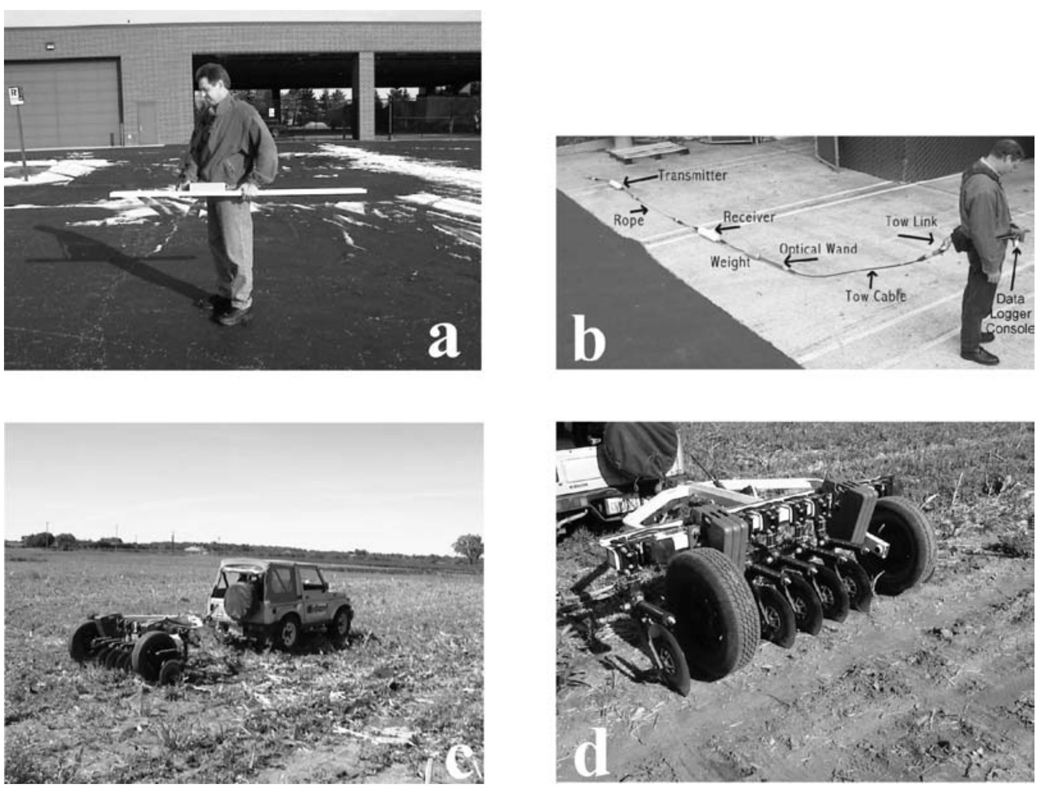

Figure 1.: (**a**) Geophex, Ltd. GEM-2 multi-frequency ground conductivity meter, (**b**) Geometrics, Inc. OhmMapper TR1 pulled electrode array resistivity measurement unit, (**c**) Veris 3100 Soil EC Mapping System, and (**d**) close-up of the Veris 3100 pulled electrode array.

Field Test Program

This research project was divided into two parts. In one part, the investigation focused on determining the relative impacts on apparent soil electrical conductivity (ECa) due to soil profile properties versus the factors associated with agricultural field operations or rainfall. Electromagnetic induction (EMI) surveys were conducted under a variety of field conditions including different controlled shallow water table depths, changes in surface moisture content due to rainfall or sprinkler irrigation, before and after fertilizer application, and additionally, before and after tillage operations. This portion of the project took place at a test plot located behind the Ohio State University (OSU) ElectroScience Laboratory (ESL) in Columbus, Ohio. This particular test plot (**Figure 2a**), denoted as ESL #1, was chosen because it was small, and therefore easily managed, and in addition, it had a subsurface drainage pipe system with two riser pipes connected up to the surface, thereby allowing a shallow water table to be maintained at any desired level through use of a Hudson valve connected at the end of a water supply hose and suspended inside one of the riser pipes. The EMI ECa measurements for this part of the study were collected along lines oriented north-south that were separated from one another by 1.5 m.

The second part of the project was devoted to gauging the similarity between different geophysical methods used to map ECa. Electromagnetic induction and two pulled electrode array resistivity methods were compared at two test plots. These two test plots were located on a portion of the OSU Waterman Agricultural and Natural Resources Laboratory near the intersection of Lane Avenue and Kenny Road in Columbus, Ohio. One of the test plots (**Figure 2b**), denoted as WATLK #1, had a functioning corrugated plastic tubing (CPT) subsurface drainage pipe system that was connected just outside the plot to a hydraulic control structure. The hydraulic control structure contained an adjustable-height weir, and water added on the upstream side of the weir would back-up into the functioning drainage pipes beneath WATLK #1, in turn raising the water table in the field. WATLK #1 had an additional clay tile subsurface drainage pipe system that was non-functioning. The second test plot, denoted as WATLK #2, did not have a functioning subsurface drainage pipe system that would allow shallow water table management. WATLK #2 was located 5 m west of WATLK #1, and its dimensions compared to WATLK #1 are the same in the north-south direction, but 6.1 m shorter in the east-west direction. A comparison of all three geophysical methods for measuring ECa was done once in the late summer of 2002 and once during the middle of fall of 2002. ECa measurements obtained at both test plots for this part of the study were collected along lines oriented north-south that were separated from one another by 3.0 m.

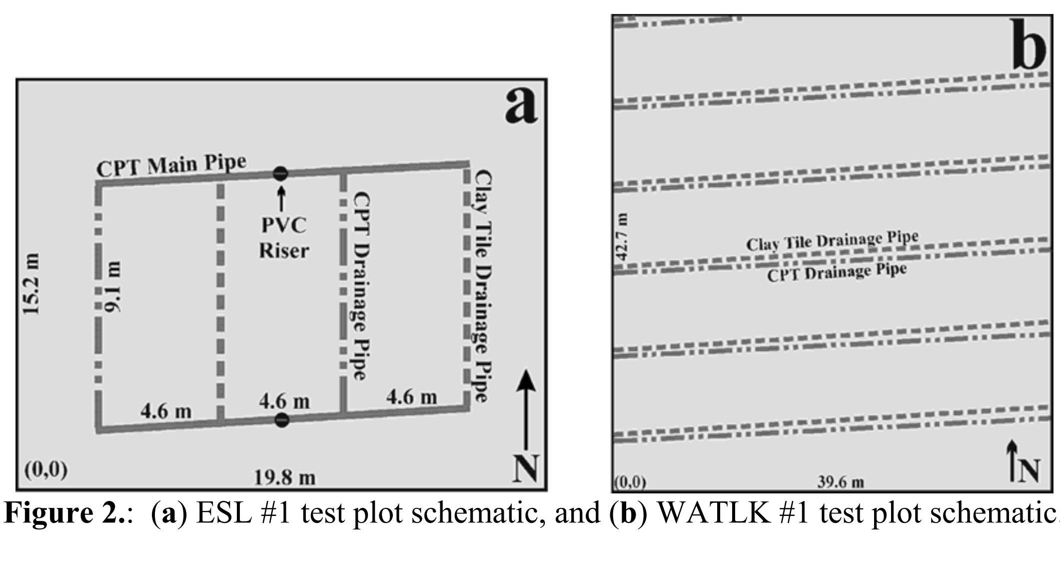

Figure 2.: (**a**) ESL #1 test plot schematic, and (**b**) WATLK #1 test plot schematic.

Results

Field conditions at all three test plots utilized in this research project were monitored with water table observation wells, a time domain reflectometry device for measuring soil surface moisture content, soil thermometers, an infrared thermometer for above ground readings, and rain gauges. The type of soil present at ESL #1 was a silty clay. The soils at WATLK #1 and WATLK #2 ranged from silty clay to clay. For statistical analysis and mapping purposes, all geophysical measurements were converted into values of mS/m. A summary of test plot field conditions and corresponding geophysical survey results for both parts of the project are provided as follows.

ESL #1 Field Conditions and EMI Results for the Part of the Project Focused on Determining the Relative Impacts on ECa Due to Soil Profile Properties Versus Factors Associated With Agricultural Field Operations or Rainfall

November 14, 2001 – Field Conditions: Test plot had been covered with a plastic tarp six weeks prior to this date in order to produce soil conditions that were as dry as possible. Both test plot observation wells were dry, so average water table depth was greater than 1 m. Air temperature near surface was approximately 16 degrees C. **Results:** Average apparent soil electrical conductivity (ECa) at a 14610 Hz instrument frequency = 14.16 mS/m, and standard deviation of ECa = 3.09 mS/m.

November 16, 2001 – Field Conditions: Test plot had been covered with a plastic tarp six weeks prior to this date in order to produce soil conditions that were as dry as possible. Both test plot observation wells were dry, so average water table depth was greater than 1 m. Air temperature near surface was approximately 16 degrees C. **Results:** Average ECa (14610 Hz instrument frequency) = 13.77 mS/m, and standard deviation of ECa = 2.98 mS/m.

July 8, 2002 – Field Conditions: Prior to this time there had been no test plot subirrigation for seven months. All nine observation wells (seven recently installed) were dry, so average water table depth was greater than 0.91 m. Average soil surface volumetric moisture content = 20.2%, soil temperature at surface = 21 degrees C, and air temperature near surface = 28 degrees C**. Results:** Average ECa (14610 Hz instrument frequency) = 10.14 mS/m, and standard deviation of ECa = 1.65 mS/m.

July 12, 2002 – Field Conditions: Subirrigation had commenced with water applied through the north riser intake pipe. The water level in the north riser intake pipe was maintained with a Hudson valve at a position 0.1 m above the bottom of the drain pipe located directly beneath the riser. Average water table depth = 0.84 m, average soil surface volumetric moisture content = 23.0%, soil temperature at surface = 20 degrees C, and air temperature near surface = 24 degrees C. **Results:** Average ECa (14610 Hz instrument frequency) = 7.37 mS/m, and standard deviation of ECa = 1.75 mS/m.

July 15, 2002 – Field Conditions: Subirrigation continued and the water level in the north riser intake pipe was maintained at a position 0.3 m above the bottom of the drain pipe located directly beneath the riser. Average water table depth = 0.62 m, average soil surface volumetric moisture content = 22.7%, soil temperature at surface = 21 degrees C, and air temperature near surface = 25 degrees C. **Results:** Average ECa (14610 Hz instrument frequency) = 8.98 mS/m, and standard deviation of ECa = 2.16 mS/m.

July 18, 2002 – Field Conditions: Subirrigation continued and the water level in the north riser intake pipe was maintained at a position 0.6 m above the bottom of the drain pipe located directly beneath the riser. Average water table depth = 0.35 m, average soil surface volumetric moisture content = 41.8%, soil temperature at surface = 23 degrees C, and air temperature near surface = 26 degrees C. **Results:** Average ECa (14610 Hz instrument frequency) = 10.36 mS/m, and standard deviation of ECa = 2.86 mS/m.

July 19, 2002 – Field Conditions: Subirrigation continued and the water level in the north riser intake pipe was maintained at a position 0.76 m above the bottom of the drain pipe located directly beneath the riser. In addition, water was added at the surface within the center portion of the test plot using a sprinkler in order to make soil conditions as wet as possible. Average water table depth = 0.27 m, average soil surface volumetric moisture content = 52.1%, soil temperature at surface = 21 degrees C, and air temperature near surface = 29 degrees C. **Results:** Average ECa (14610 Hz instrument frequency) = 13.33 mS/m, and standard deviation of ECa = 2.87 mS/m.

July 26, 2002 – **Field Conditions:** Subirrigation had been discontinued seven days prior to this date. Average water table depth = 0.78 m, average soil surface volumetric moisture content = 39.7%, soil temperature at surface = 20 degrees C, and air temperature near surface = 27 degrees C. **Results:** Average ECa (14610 Hz instrument frequency) = 13.80 mS/m, and standard deviation of ECa = 2.60 mS/m.

August 7, 2002 – Field Conditions: Subirrigation had been discontinued 19 days prior to this time. **Results:** Average ECa (14610 Hz instrument frequency) = 13.49 mS/m, and standard deviation of ECa = 2.51 mS/m.

August 10, 2002 – **Field Conditions:** Subirrigation had been recommenced three days prior to this date, and the water level in the north riser intake pipe was maintained at a position 0.6 m above the bottom of the drain pipe located directly beneath the riser. Average water table depth = 0.32 m, and average soil surface volumetric moisture content = 47.4%. **Results:** Average ECa (14610 Hz instrument frequency) = 13.92 mS/m, and standard deviation of ECa = 3.06 mS/m.

August 18, 2002 – **Field Conditions:** Subirrigation had been discontinued eight days prior to this date. Average water table depth = 0.87 m, average soil surface volumetric moisture content = 34.8%, soil temperature at surface = 24 degrees C, and air temperature near surface = 24 degrees C. **Results:** Average ECa (14610 Hz instrument frequency) = 13.11 mS/m, and standard deviation of ECa = 5.96 mS/m.

August 29, 2002 – **Field Conditions:** A test plot application of 45.5 kg of 12-12-12 fertilizer was done eleven days before this date. In addition, for one day prior to this EMI survey, water was applied evenly to the test plot surface with two sprinklers in order to dissolve the fertilizer and let it soak into the ground. Average water table depth = 0.35 m, average soil surface volumetric moisture content = 47.7%, soil temperature at surface = 22 degrees C, and air temperature near surface = 27 degrees C. **Results:** Average ECa (14610 Hz instrument frequency) = 14.96 mS/m, and standard deviation of ECa = 3.09 mS/m.

September 8, 2002 – **Field Conditions:** As a supplement to the 45.5 kg of fertilizer already applied, 22.7 kg of 21-28-7 starter fertilizer were added to the test plot eight days before this date. Directly after this second fertilizer application, the test plot was evenly watered with two sprinklers for one day in order to dissolve the fertilizer and let it soak into the ground. Average water table depth = 0.87 m, average soil surface volumetric moisture content = 29.2%, soil temperature at surface = 23 degrees C, and air temperature near surface = 33 degrees C. **Results:** Average ECa (14610 Hz instrument frequency) = 13.15 mS/m, and standard deviation of ECa = 2.38 mS/m.

September 11, 2002 – **Field Conditions:** As a supplement to the 68.2 kg of fertilizer already applied, 22.7 kg of 21-28-7 starter fertilizer were added to the test plot three days before this date. Directly after this third fertilizer application, the test plot was evenly watered with two sprinklers for three days in order to dissolve the fertilizer and let it soak into the ground. Average water table depth = 0.66 m, average soil surface volumetric moisture content = 58.3%, soil temperature at surface = 15 degrees C, and air temperature near surface = 20 degrees C. **Results:** Average ECa (14610 Hz instrument frequency) = 16.67 mS/m, and standard deviation of ECa = 2.87 mS/m.

September 19, 2002 – **Field Conditions:** By this date, 91 kg of fertilizer had been added to the test plot. Rainfall during the preceding week totaled 44 mm causing moist surface conditions. Average water table depth = 0.82 m, Average soil surface volumetric moisture content = 52.0%, soil temperature at surface = 22 degrees C, and air temperature near surface = 24 degrees C. **Results:** Average ECa (14610 Hz instrument frequency) = 17.20 mS/m, and standard deviation of ECa = 2.52 mS/m.

September 21, 2002 – Field Conditions: On this date, just prior to EMI surveying, the test plot was tilled twice down to a depth of 15 cm. Average water table depth = 0.77 m, average soil surface volumetric moisture content = 51.3%, soil temperature at surface = 21 degrees C, and air temperature near surface = 27 degrees C. **Results:** Average ECa (14610 Hz instrument frequency) = 15.70 mS/m, and standard deviation of ECa = 2.38 mS/m.

October 7, 2002 – Field Conditions: No new field operations (subirrigation, fertilization, or tillage) had been conducted since the last EMI survey seventeen days prior to this date. Average water table depth = 0.85 m, average soil surface volumetric moisture content = 45.7%, soil temperature at surface = 15 degrees C, and air temperature near surface = 14 degrees C. **Results:** Average ECa (14610 Hz instrument frequency) = 17.49 mS/m, and standard deviation of ECa = 1.98 mS/m.

November 20, 2002 – Field Conditions: No new field operations (subirrigation, fertilization, or tillage) had been conducted for two months prior to this date. EMI surveys were conducted in the early morning, noon, and late afternoon. Average water table depth = 0.86 m, average soil surface volumetric moisture content = 42.9%, and air temperature near surface ranged from 4 degrees in the early morning to 14 degrees C in the late afternoon. **Results:** In the early morning, the average ECa (14610 Hz instrument frequency) = 13.21 mS/m, and the standard deviation of ECa = 1.66 mS/m. At noon, the average ECa (14610 Hz instrument frequency) = 14.20 mS/m, and the standard deviation of ECa = 1.61 mS/m. Late in the afternoon, the average ECa (14610 Hz instrument frequency) = 13.94 mS/m, and the standard deviation of ECa = 1.62 mS/m.

WATLK #1 and WATLK #2 Field Conditions and Results for the Part of the Project Focused on Evaluating the Consistency Between Different Geophysical Methods Used to Map ECa

August 5-14, 2002

Field Conditions:

1) Weather conditions were fairly dry the week prior, and the amount of rainfall during this period was 38 mm.
2) At this time, there were ten observation wells in WATLK #1 installed to an average depth of 0.8 m. Five observation wells for WATLK #2 were installed later, on Aug. 31, 2002. Seven out of the ten WATLK #1 observation wells were dry throughout this period. The other three had average water table depths of 0.75, 0.78, and 0.81 m.
3) The average soil surface volumetric moisture content for WATLK #1 during this time was 36.5%. For WATLK #2, the average soil surface volumetric moisture content was 44.5%.
4) Surface soil temperatures ranged from 20 to 28 degrees C.
5) Air temperatures near the surface ranged from 23 to 32 degrees C.

Results:

<u>WATLK #1 Average ECa (Avg. ECa) and Standard Deviation of ECa (Std. Dev. ECa):</u>

1) Geophex, Ltd. GEM-2 ground conductivity meter electromagnetic induction (EMI) method,
   14610 Hz instrument frequency – Avg. ECa = 18.41 mS/m, Std. Dev. ECa = 5.85 mS/m,
2) Geometrics, Inc. OhmMapper TR1 pulled electrode array resistivity method,
   2.5 m dipole separation - Avg. ECa = 49.68 mS/m, Std. Dev. ECa = 12.91 mS/m,
3) Veris 3100 Soil EC Mapping System pulled electrode array resistivity method,
   deep (0.9 m) soil measurements - Avg. ECa = 35.56 mS/m, Std. Dev. ECa = 6.95 mS/m.

<u>WATLK #2 Avg. ECa and Std. Dev. ECa:</u>

1) Geophex, Ltd. GEM-2 ground conductivity meter EMI method,
   14610 Hz instrument frequency – Avg. ECa = 14.36 mS/m, Std. Dev. ECa = 5.14 mS/m,

2) Geometrics, Inc. OhmMapper TR1 pulled electrode array resistivity method,
   2.5 m dipole separation - Avg. ECa = 35.1 mS/m, Std. Dev. ECa = 5.71 mS/m,
3) Veris 3100 Soil EC Mapping System pulled electrode array resistivity method,
   deep (0.9 m) soil measurements - Avg. ECa =29.28 mS/m, Std. Dev. ECa =6.83 mS/m.

October 2-5, 2002

Field Conditions:

1) On Oct. 2, 2002, there was 89 mm of water in the rain gauges at the WATLK test plot(s) indicating that there was a substantial amount of precipitation in the days prior to this time. During the period, there was an additional 16.5 mm of rainfall.
2) WATLK #1 had been subirrigated for over a month before Oct. 2, 2002. The water level in the weir-type hydraulic control structure was maintained at a position 0.76 m above the bottom of the control structure on its upstream side.
3) The average water table depth in WATLK #1 during Oct 2-5, 2002 was 0.58 m. The water table in WATLK #1 was not level, but rather undulating, it typically being 0.3 m higher over the drain lines than it was at locations midway between them. The average water table depth in WATLK #2 at this time was 0.87 m.
4) The average soil surface volumetric moisture content for WATLK #1 was 52.2%. For WATLK #2, the average soil surface volumetric moisture content was 51.6%.
5) Surface soil temperatures ranged from 15 to 19 degrees C.
6) Air temperatures near the surface ranged from 13 to 27 degrees C.

Results:

<u>WATLK #1 Avg. ECa and Std. Dev. ECa:</u>

1) Geophex, Ltd. GEM-2 ground conductivity meter EMI method,
   8190 Hz instrument frequency – Avg. ECa = 33.68 mS/m, Std. Dev. ECa = 6.56 mS/m,
   14610 Hz instrument frequency – Avg. ECa = 31.11 mS/m, Std. Dev. ECa = 5.82 mS/m,
   20010 Hz instrument frequency - Avg. ECa = 33.76 mS/m, Std. Dev. ECa = 5.68 mS/m,
2) Geometrics, Inc. OhmMapper TR1 pulled electrode array resistivity method,
   0.625 m dipole separation - Avg. ECa = 46.22 mS/m, Std. Dev. ECa = 13.79 mS/m,
   1.25 m dipole separation - Avg. ECa = 43.99 mS/m, Std. Dev. ECa = 12.43 mS/m,
   2.5 m dipole separation - Avg. ECa = 38.73 mS/m, Std. Dev. ECa = 9.65 mS/m,
   5.0 m dipole separation - Avg. ECa = 31.46 mS/m, Std. Dev. ECa = 6.23 mS/m,
3) Veris 3100 Soil EC Mapping System pulled electrode array resistivity method,
   shallow (0.3 m) soil measurements - Avg. ECa = 38.69 mS/m, Std. Dev. ECa = 3.80 mS/m,
   deep (0.9 m) soil measurements - Avg. ECa = 49.32 mS/m, Std. Dev. ECa = 5.88 ms/m.

<u>Test Plot #2 Avg. ECa and Std. ECa:</u>

1) Geophex, Ltd. GEM-2 ground conductivity meter EMI method,
   14610 Hz instrument frequency – Avg. ECa = 26.46 mS/m, Std. Dev. ECa = 3.72 mS/m,
2) Geometrics, Inc. OhmMapper TR1 pulled electrode array resistivity method,
   2.5 m dipole separation - Avg. ECa = 29.94 mS/m, Std. Dev. ECa = 5.14 mS/m,
3) Veris 3100 Soil EC Mapping System pulled electrode array resistivity method,
   deep (0.9 m) soil measurements - Avg. ECa = 46.51 mS/m, Std. Dev. ECa = 5.59 mS/m.

Discussion

Impact of Field Conditions on EMI Measured ECa

Electromagnetic induction (EMI) apparent soil electrical conductivity (ECa) results were quite similar regardless of instrument frequency, therefore discussion will concentrate on data obtained at 14610 Hz. The shallow hydrologic condition impacts were assessed through a linear regression analysis between average ECa versus average water table depth and average ECa versus average soil surface volumetric moisture content. The ESL #1 EMI survey data incorporated into this statistical analysis included only that which was obtained on days where there was sufficient water table and/or soil surface moisture information available. The linear regression analysis, coefficient of determination (R^2) for ECa versus water table depth was 0.00, and for ECa versus soil surface volumetric moisture content it was 0.67. Although the correlation between ECa and soil surface moisture is definitely significant, it is probably not strong enough to warrant using ECa as a direct predictor of volumetric moisture content at the ground surface. This same ECa data exhibited only minor correlation to either soil temperature ($R^2 = 0.15$) or air temperature ($R^2 = 0.09$).

There were three uniform fertilizer applications on ESL #1, the first on August 18, 2002 and the last on September 8, 2002. A total of 15 kg nitrogen, 18 kg phosphorous, and 9 kg of potassium were added to the test plot. This is approximately 3 times the nitrogen, 9 times the phosphorous, and 5 times the potassium that would normally be applied to a crop of field corn grown in central Ohio on a plot of the same size. ECa averaged 13.53 mS/m and the mean soil surface volumetric moisture content was 43.5% in the five EMI surveys conducted four weeks prior to the first fertilizer application. In the six EMI surveys done within seven weeks following the first fertilizer application, ECa averaged 15.86 mS/m and the mean soil surface volumetric moisture content was 47.4%. Since mean soil surface moisture conditions were very similar in the four week period before and the seven week period after the first fertilizer application, it appears that adding nitrogen, phosphorous, and potassium crop nutrients to the test plot modestly increased its average ECa by a little over 2 mS/m. Ten weeks after the final fertilizer application, the ESL #1 average ECa was 13.78 mS/m with a mean soil surface volumetric moisture content of 42.9%, suggesting that dissolution and leaching may make the impact of fertilizer application on ECa relatively short-lived.

Tillage operations were conducted at ESL #1 twice on the same day with the soil uniformly loosened and disaggregated down to a depth 15 cm. Two days prior to tillage, on September 19, 2002, the average ECa was 17.20 mS/m, with a corresponding mean soil surface moisture content of 52.0%. On September 21, 2002, just three hours after the test plot was tilled, the average ECa was down to 15.70 mS/m, while the mean soil surface volumetric moisture content remained almost unchanged at 51.3%. Seventeen days after tillage, while the soil was still in a loosened, disaggregated state, average ECa was back up to 17.49 mS/m, with the corresponding mean soil surface moisture content still not having changed much at 45.7%. These EMI results, at comparable soil surface moisture conditions, suggest that the impact of tillage operations on ECa is most likely minimal, and what little (if any) effect does occur is of a magnitude similar to instrument drift, which over an eight hour period on November 20, 2002 was observed to be approximately 1 mS/m.

Perhaps the most important finding from this part of the project is that the overall spatial ECa pattern remained relatively consistent regardless of field conditions. This is illustrated (**Figure 3**) by comparing ESL #1 ECa maps for November 16, 2001 (moderately dry conditions), July 8, 2002 (very dry conditions), July 19, 2002 (very wet conditions), September 11, 2002 (three days after the final fertilizer application), September 21, 2002 (just three hours after tillage), and November 20, 2002 (ten weeks after the final fertilizer application and 9 weeks after tillage). As shown, the lowest ECa values on any ESL #1 map are along the northern boundary. The next lowest values are adjacent to the southern boundary. Higher ECa numbers are found within a tongue-shaped area that extends westward from the east boundary for almost three quarters of the test plot length. This ECa spatial pattern consistency, which is evident regardless of the field conditions, is a strong indication that soil profile properties tend to dominate the ECa response measured by near-surface geophysical methods. This can be further emphasized through comparison of the July 19, 2002 and September 21, 2002 ECa contour maps exhibiting similar spatial patterns (**Figures 3c and 3e**) and the corresponding water table and soil surface moisture content contour maps for those two days, which depict quite different shallow hydrologic conditions (**Figure 4**). On July 19, 2002 the water table (**Figure 4a**) was mounded to the surface over the central portion of the test plot directly above the subsurface drainage pipe system (**Figure 2a**), while along the periphery of ESL #1, with the exception of the southeast corner, the soil surface was dry (**Figure 4c**) and the water table much lower. The shallow hydrologic conditions on September 21, 2002, unlike those for July 19, 2002, were relatively uniform, with all water table depths greater than 0.6 m (**Figure 4b**), and high soil surface volumetric moisture contents within a somewhat narrow range of 43% to 57% (**Figure 4d**). Consequently, the similar ECa spatial patterns for ESL #1 on July 19, 2002 and September 21, 2002, at times when the shallow hydrologic conditions on those two days were very different, is compelling evidence, since there are no other possible explanations, that the most important item impacting the ECa response has to be soil profile properties.

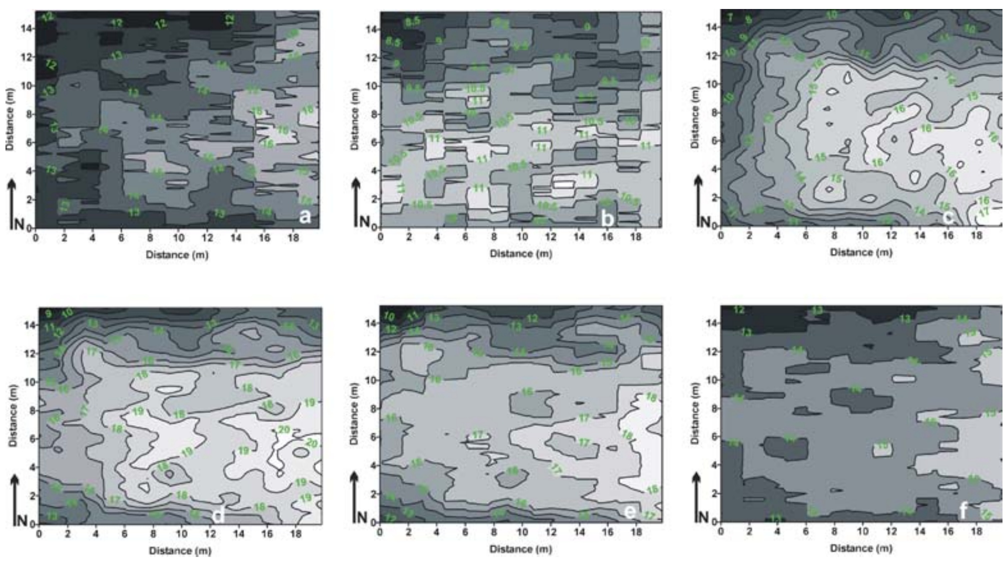

Figure 3.: ECa contour maps for (**a**) November 16, 2001, (**b**) July 8, 2002, (**c**) July 19, 2002, (**d**) September 11, 2002, (**e**) September 21, 2002, and (**f**) November 20, 2002. The contour interval for all maps is 1 mS/m with the exception of the July 8, 2002 map which had a contour interval of 0.5 mS/m.

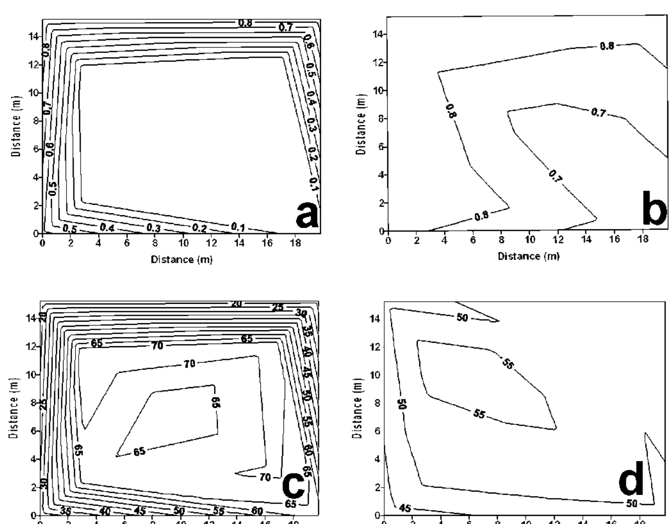

Figure 4.: Shallow hydrologic conditions, (**a**) water table depths for July 19, 2002, (**b**) soil surface volumetric moisture contents for July 19, 2002, (**c**) water table depths for September 21, 2002, and (**d**) soil surface volumetric moisture contents for September 21, 2002. The contour interval for water table depth is 0.1 m, and for soil surface volumetric moisture content it is 5%.

Comparison of Different Geophysical Methods for Measuring ECa

Although the overall average test plot ECa values differed (see Results section), the three different geophysical methods produced comparable results with respect to ECa spatial patterns. This is depicted in the ECa contour maps for WATLK #1 (**Figure 5**) and WATLK #2 (**Figure 6**) created from data collected during the period of October 2-5, 2002. The WATLK #1 ECa maps provide a complete comparison of GEM-2 EMI surveying at 8190, 14610, an 20010 Hz instrument frequencies (**Figures 5a, 5b, and 5c**), OhmMapper TR1 pulled electrode array resistivity surveying at 0.625, 1.25, 2.5, and 5 m dipole-dipole separations (**Figures 5d, 5e, 5f, and 5g**), and Veris 3100 Soil EC Mapping System pulled electrode array resistivity surveying for shallow and deep soil measurements (**Figures 5h and 5i**). As shown, all WATLK #1 contour maps, when compared, seem to correlate well regarding spatial ECa trends, with the exception of the one generated from VERIS 3100 EC Mapping System shallow soil measurements. Likewise, ECa contour maps from the three near-surface geophysical methods show good similarity for WATLK #2 (**Figures 6a, 6b, and 6c**).

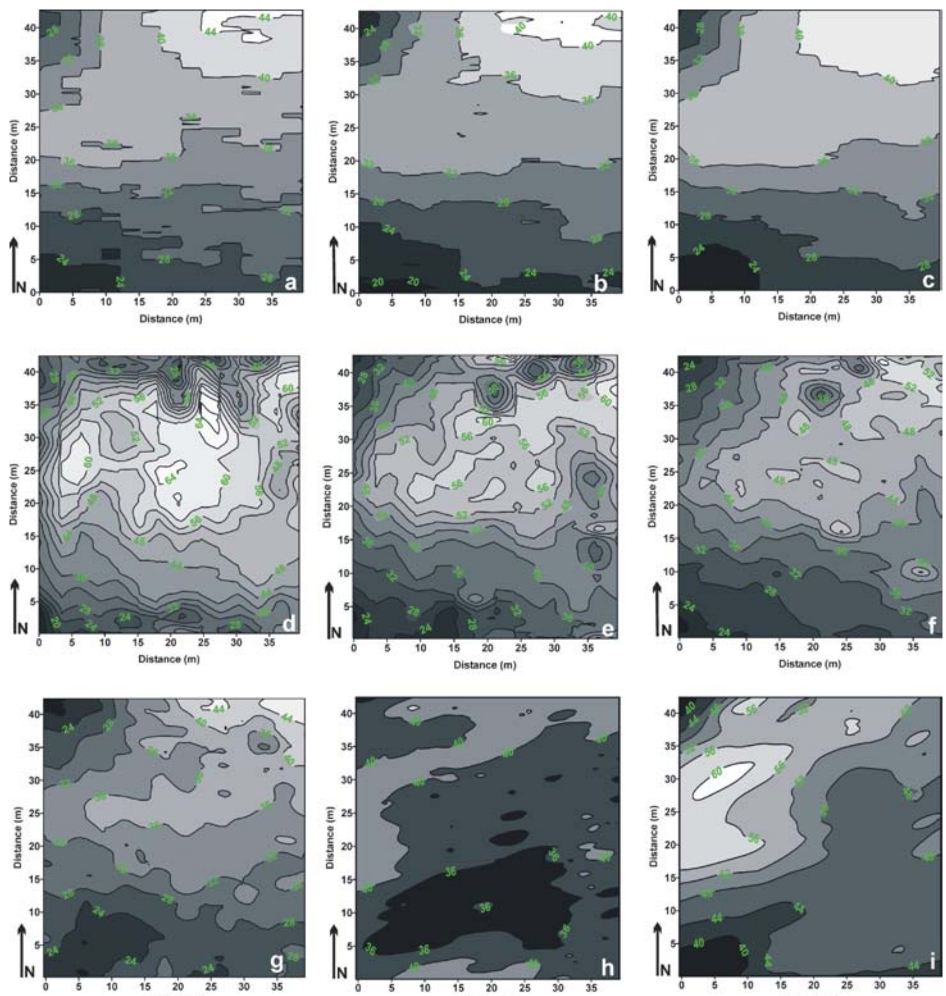

Figure 5.: WATLK #1 ECa contour maps for the period of October 2-5, 2002, (**a**) GEM-2, 8190 Hz instrument frequency, (**b**) GEM-2, 14610 Hz instrument frequency, (**c**) GEM-2, 20010 Hz instrument frequency, (**d**) OhmMapper TR1, 0.625 m dipole-dipole separation, (**e**) OhmMapper TR1, 1.25 m dipole-dipole separation, (**f**) OhmMapper TR1, 2.5 m dipole-dipole separation, (**g**) OhmMapper TR1, 5 m dipole-dipole separation, (**h**) VERIS 3100 EC Mapping System, shallow (30 cm) soil measurements, and (**i**) VERIS 3100 EC Mapping System, deep (90 cm) soil measurements. Contour interval is 4 mS/m.

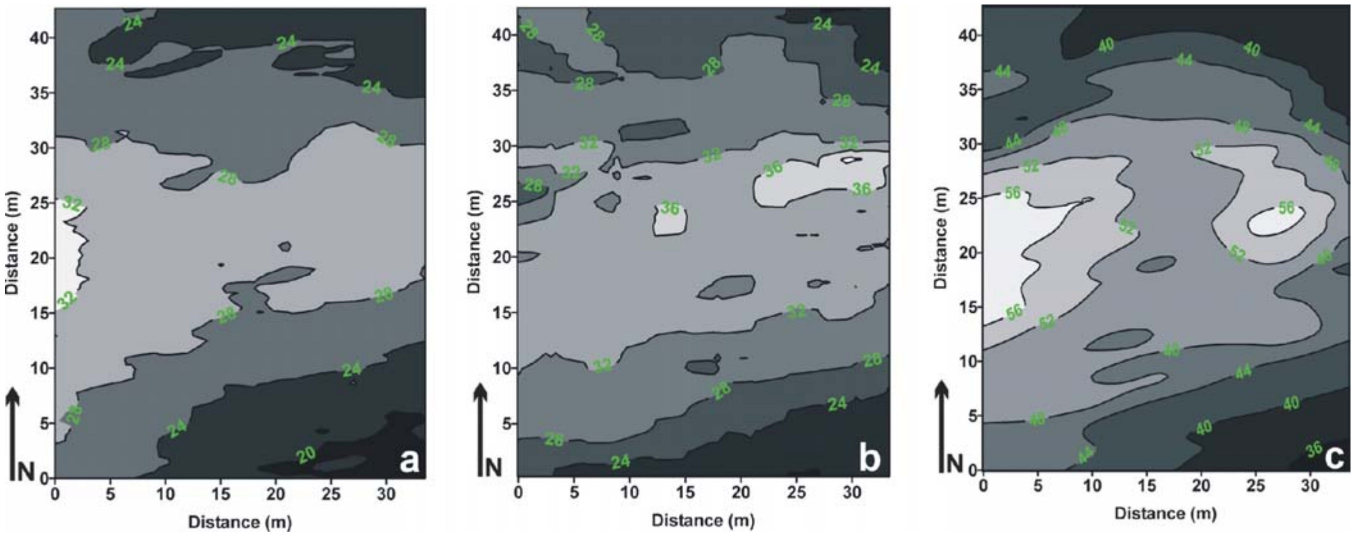

Figure 6.: WATLK #2 ECa contour maps for the period of October 2-5, 2002, (**a**) GEM-2, 14610 Hz instrument frequency, (**b**) OhmMapper TR1, 2.5 m dipole-dipole separation, and (**c**) VERIS 3100 EC Mapping System, deep (90 cm) soil measurements. Contour interval is 4 mS/m.

Consequently, all three geophysical methods appear equally capable of producing valid results with respect to mapping spatial ECa trends. This information can then be used for the important task of gauging changes in soil profile properties, and hence soil fertility, from one field location to another. One nice aspect of the OhmMapper TR1 data is that it lends itself well to least-square inversion methods, such as those described by Sasaki [13], developed for traditional resistivity survey measurements, which in turn allow ECa depth profiles to be easily generated (**Figure 7**).

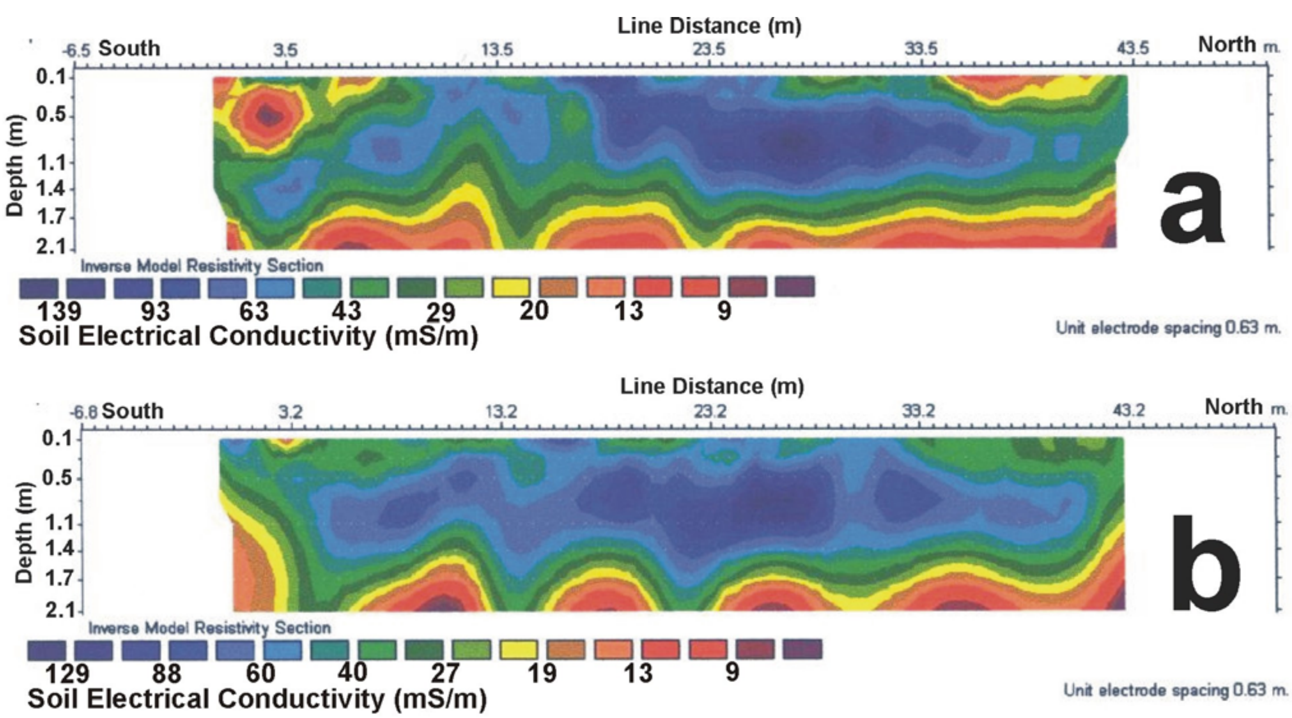

Figure 7.: WATLK #1 ECa depth profiles created with the computer inversion software, RES2DINV, developed by Loke [14] using OhmMapper TR1 data collected on August 5, 2002, (**a**) the west test plot boundary, and (b) a line 3 m east of the west test plot boundary.

Summary

Electromagnetic induction (EMI) and two different pulled electrode array resistivity methods were used to map apparent soil electrical conductivity (ECa) on three different Columbus, Ohio agricultural test plots having fine-grained glacially derived soils. All three geophysical methods appeared to work equally well when evaluated on the two test plots. Here, although the average test plot ECa values differed between the three methods, spatial ECa patterns, when compared, were quite similar. EMI surveys conducted on a separate test plot showed ECa to be significantly correlated to soil surface volumetric moisture content ($R^2 = 0.67$), but not shallow water table depth ($R^2 = 0.00$), surface soil temperature ($R^2 = 0.15$), or surface air temperature ($R^2 = 0.09$). EMI data from the same test plot indicates that higher than normal fertilizer application can modestly increase ECa, however, tillage operations appear to have little impact. Most notably, the same EMI data showed that, regardless of the field conditions present, ECa spatial patterns remain consistent, which in turn provides strong evidence that soil profile properties dominate the ECa response. This is important from the standpoint of precision agriculture in Great Lakes region locales with glacially derived soils, because it implies that geophysical ECa mapping can delineate spatial changes in soil profile properties that are often related to soil fertility. This information can then be utilized to apply just the right amount of fertilizer, soil amendments, pesticides, herbicides, and tillage effort to different areas of the field, thereby optimizing crop yields while reducing input costs.

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